Long-Term Impacts of Forest Harvesting Related Soil Disturbance on Log Product Yields and Economic Potential in a New Zealand Forest

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The effect of soil disturbance (litter removal, topsoil removal and compaction) from forest harvesting on the productivity, log product yields and economic potential of second-rotation *Pinus radiata* growing on a clay loam soil, was assessed in a long-term trial 21 years after planting. The results are projected forward to the expected harvest age of 28 years. Relative to control plots, average tree volume at 21 years was reduced by 8% in the plots where the litter had been removed and the topsoil had been compacted, and by up to 42% in the plots where the topsoil had been removed and the subsoil compacted. The "degree of compaction" did not have a significant effect on average tree volume in the plots where litter had been removed but did have a significant effect where the topsoil had been removed. Per tree economic potential was reduced to a greater extent (up to 60% loss in value) than average tree volume was reduced. This was largely due to changes in log product yield distribution. Projecting tree growth forward to the end of the rotation at age 28 indicated that the impacts of soil disturbance on tree growth, economic potential and log product yields are likely to be similar in relative terms to those found at age 21.

Keywords harvesting, *Pinus radiata*, tree growth, litter removal, compaction
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1 Introduction

Ground-based logging equipment such as felling machines, mechanical processors, skidders and crawler tractors are used to harvest forests in many parts of the world. This equipment may travel over two-thirds of a site (McMahon et al. 1999). It may cause soil disturbance by displacing or mixing litter and soil, and/or compacting the soil. Removal of litter and soil alters the amount and availability of nutrients. Compaction and removal of topsoil can alter root volume by increasing resistance to root growth or reducing the ability of the soil to supply oxygen and water to plant roots. Not all soil disturbance on a harvesting site is the same. Murphy (1984) noted from a survey of 19 harvesting operations in New Zealand that "deep" disturbance covered from 5 to 25% of the harvest area and was affected by such factors as slope, type of harvesting equipment and planning.

Many trials and a number of worldwide literature reviews have shown that soil disturbance and compaction resulting from harvesting often increase seedling mortality and reduce tree growth (Murphy 1982, Grey and Jacobs 1987, Skinner et al. 1989, Minore and Weatherley 1990, Wronski and Murphy 1994). In particular, the effects of soil compaction may last for decades unless remedial action is taken. Modification of the soil as a result of harvesting is of particular importance where fast growing species or multiple entry thinnings are utilised.

Stewart et al. (1988) developed a model for evaluating the economic impacts of soil disturbance. Cost-benefit analyses of various ground-based harvesting practices, such as the use of designated skidtrails, could be estimated using their model. Their model only considered compaction effects. It also did not take into account the effect of compaction on log-product yields; for example, in their analyses a 5% drop in volume equated directly to a 5% drop in value.

In 1982 the New Zealand Forest Research Institute established a trial (1) to investigate the short-term and long-term impacts of soil disturbance on soil properties and second-rotation radiata pine (*Pinus radiata* D.Don) tree growth and (2) to assess the long term effects on tree economic potential. This paper reports on the impacts on tree growth and economic potential of the trees 21 years after establishment and forecasts the effects through to age 28 years when the trees are expected to be harvested.

2 Materials and Methods

2.1 Site

The trial is located in Maramarua Forest, New Zealand, on rolling terrain with Ultic soils (NZ soil classification, Hewitt 1993) or Typic Hapludults (US classification). Ultic soils are common on old landscapes in the northern third of the North Island. Soils at the trial site are developed from highly weathered greywacke and dominated by kaolinitic and halloysitic clays. Shallow clay-loam topsoil overlies mottled, slowly-permeable subsoil. The soils are acidic with low native chemical fertility, particularly phosphorus (P); however P levels at the trial site reflect fertilisation of both the first rotation plantation and 110 kg P ha^{-1} applied during the first year of the trial. The climate at Maramarua Forest is mild and humid, with a mean annual rainfall of 1280 mm and small soil moisture deficits from November to February on average. The growing season for radiata pine in this part of New Zealand is 12 months per year. Mature stands of fertilised radiata pine in Maramarua Forest have a standing volume of 700 to 800 m^3 per ha and are harvested after 25 to 29 years.

2.2 Site Preparation

The pre-study stand was harvested with a cable logging system. The trial was located on a flatter portion (0 to 10% slopes) of the harvest unit which had received minimal soil impacts from the cable logging operation. Blocking of areas was also undertaken to ensure minimal differences in initial site conditions for each treatment replication. The trial layout is detailed in Skinner et al. (1989).

Treatments were selected to match the minimal through to severe impact ratings of the visual classification system used by Murphy (1982) to classify soil disturbance after harvesting forests.

Five treatments were replicated five times in a randomised complete block design. Each treatment was applied evenly across the whole surface of the 30 m × 20 m plot. Soil and litter removed from the 0.06 ha plots was windrowed into a 10 m buffer strip between adjacent plots. Measurements at age 15 years showed that growth of trees adjacent to windrows was not significantly different from trees in the central core of each plot; indicating that edge trees were not exploiting the more favourable conditions in the windrows. The treatments in descending order of soil disturbance were:

i) *Topsoil removed with a small bulldozer and subsoil heavily compacted with eight passes of a loader (TR-HC)*. The topsoil was about 10 cm deep. This treatment is equivalent to Disturbance Class (DC) 4 under the visual classification system described by Murphy (1982) and is usually associated with landings or with skid trails that have had much traffic over them.
ii) *Topsoil removed with a small bulldozer and subsoil lightly compacted with two passes of a loader (TR-LC)*. This treatment is equivalent to DC3 under the visual classification system and is usually associated with skid trails that have had a medium amount of traffic over them.
iii) *Forest litter removed by a small bulldozer; light compaction (LR-LC)*. This treatment is equivalent to DC2 under the visual classification system and is usually associated with skid trails that have had a small amount of traffic over them.
iv) *Forest litter removed by hand; no soil compaction (LR-NC)*. There is no equivalent disturbance class under the visual classification system. This treatment was included to see what impact forest litter removal had on growth but it also simulates removal of the litter layer by a log dragged over the ground.
v) *Control*. This treatment is equivalent to DC0 under the visual classification system and is associated with undisturbed areas.

The visual disturbance classification system includes a DC1 category, where the harvesting machine has driven over a piece of ground, maybe only one or two times, but did not break through the litter layer. No equivalent treatment was included in this trial.

Two small, steel-tracked bulldozers were used to remove the litter layer and topsoil; a Bristol Taurus dozer (45 HP; mass unknown) and an Allis Chalmers HD6 (75 HP; ~5700 kg). The rubber-tyred front end loader used to compact the subsoil was a Hough 65 Payloader (~9300 kg).

The weed pampas grass (*Cortaderia selloana*) can be a problem during the establishment of radiata pine in Maramarua Forest. Before planting, the whole site was sprayed with hexazinone (5 kg ha^{-1}). New pampas growth was removed annually to age 10 by spot spraying with 2% glyphosate (0.7% active ingredient). Since age 10, pampas plants have been removed manually.

2.3 Second Rotation Establishment and Management

Radiata pine seedlings (1/0 stock) which had been hand-lifted and root trimmed were planted at a rate of approximately 90 per plot (3 m × 2 m spacing; 1700 stems ha^{-1}). After planting, 170 g of super phosphate was applied by hand around each seedling. Diammonium phosphate (250 g/tree) was applied one year later by the same method.

Canopy closure was noted in Control plots at age four. To prevent unequal crown competition due to treatment, all plots were thinned to approximately 600 stems ha^{-1} at age four. Small and atypical trees were selected for removal. Atypical trees were defined as those present in microsites that were not representative of the treatment, e.g., where topsoil had not been completely removed around the stumps of first-rotation trees.

At age four all residual trees were pruned, half of the green crown being removed regardless of tree height. At age five a second pruning was carried out to the same prescription. A second thinning at age six resulted in a nominal final crop stocking of 250 stems ha^{-1} (treatment means ranged between 244 and 251 stems ha^{-1}).

2.4 Growth Assessments

The heights of all trees were measured annually from age one to age six and again at ages 11, 15 and 21. Heights were measured immediately before and after each thinning if a thinning occurred in that year. Diameter at breast height measurements were made from age four at the same time as tree height measurements. These data were used to determine individual tree volume from a volume table (No. T009; Dunlop 1995). Results up to age 11 are reported in Skinner et al. (1989) and Murphy et al. (1997).

The age 21 measurements were taken on a 0.03 ha per plot "central core" of trees to minimise the possibility of any edge effects between the treatments and the buffer strips between plots. The plot size was collapsed to a central core even though earlier measurements indicated that edge effects were not evident at age 15 years. After mortality, two thinnings and a reduction in plot size to a central core, the median number of trees per plot assessed at age 21 was nine; ranging from five to eleven. The average density of residual trees was 334, 300, 286, 266 and 240 stems ha^{-1} for the TR-HC, TR-LC, LR-LC, LR-NC and Control treatments respectively. The overall average stand density for all plots was 285 stems ha^{-1}.

2.5 Product Yield and Economic Assessments

At age 21 all trees in the central core plots were assessed for height, diameter and changes in quality up the stem using the MARVL inventory system (Deadman and Goulding 1979; Manley et al. 1987). The MARVL program calculates the product yields from, and economic potential of, each tree by combining the detailed stem descriptions with log specifications in a price-driven optimal bucking routine. The optimal bucking routine selects the set of log-types that will maximize the value obtained from each stem. A set of log specifications and stumpage prices, which were representative of log markets in the first quarter of 2003, were used in the MARVL analyses (Table 1). Log specifications include such features as log dimensions, knot size, presence or absence of pruning, ovality, scarring and sweep. Stumpage prices are mill-door prices less logging and transportation costs. Logging cost curves are relatively flat for tree sizes greater than 1 m^3. Since all treatments had mean tree sizes greater than 1 m^3 no special allowance was made for tree size differences in the stumpage prices.

The MARVL system includes the means to grow a forest inventory forward to a specified age and determine the expected product yields and economic potential from the older trees. The Control plots were grown forward to age 28 using the NAPIRAD growth model (Goulding 1995). Disturbed plots were grown forward using two sets of growth trajectories.

One set of trajectories was based on the same percentage gaps (SG) among the average basal areas of the Control and the disturbance treatments on a per hectare basis at age 21. The SG trajectories for basal area at age 28 were 109%, 109%, 84% and 79% of the Control respectively for LR-NC, LR-LC, TR-LC and TR-HC.

Table 1. Log specifications and stumpage prices used to assess economic potential and product yields.

Log grade		Lengths (m)	Small end diameter (cm)		Large end diameter (cm)	Maximum knot size (cm)	Stumpage value [a)] (NZ$/m³)
			Minimum	Maximum	Maximum		
Pruned							
Export sawlogs		4.1	30	90	90	0	160
Domestic sawlogs		3.7, 4.3	30	90	90	0	135
Unpruned							
Export sawlogs	A grade	8.1, 12.1	20	34	80	14	65
	K grade	7.4, 11.1	20	26	90	14	53
Domestic sawlogs	Small branches	4.3, 6.1	30	90	90	7	63
	Large branches	5.5	20	90	90	14	50
Pulp (random length)		3.7–6.1	10	90	90	Not applicable	8

a) NZ$1 ~ US$0.54 or EUR0.51 during the first quarter of 2003.

There is some indication that the percent basal area gap between treatments and the Control is narrowing with time on a per tree basis. The second set of trajectories is based on the trend over the past decade for this narrowing gap (NG). The NG trajectories for basal area per hectare at age 28 were 108%, 112%, 95% and 90% of the Control respectively for LR-NC, LR-LC, TR-LC and TR-HC.

Significant differences ($p<0.05$) in growth and economic potential between treatments were identified by analysis of covariance, and means were compared using the least significant difference test (SAS Version 8, Procedure MIXED, Difference of Least Squares Means; SAS Institute, Cary, NC). Number of stems per hectare was used as the covariate because of inequalities in this variable between plots.

The difference in net present value (NPV) per hectare at the end of the rotation between the Control and each treatment represents the maximum additional amount that could be spent on either preventing soil disturbance during harvesting or remedial activity after the harvest. An inflation-free discount rate of 3.25% was used to calculate the NPV ha^{-1} based on the SG and NG growth trajectories to age 28.

3 Results

Results are presented in three sections: growth, economic potential and product yields at age 21; long-term trends in growth up to age 21; and projected impacts of disturbance on economic potential and product yields at age 28.

3.1 Impacts of Soil Disturbance at Age 21

3.1.1 Tree Size and Stand Volume at Age 21

Mean tree height, diameter and volume at age 21 were not affected by the number of trees per hectare in each plot. They were also not affected by removal of the litter layer at the time of planting where there had been no compaction of the topsoil (Table 2). The effect of the other treatments on some tree size parameters was still apparent, however. On treatments where the topsoil had been removed and the subsoil compacted, diameter was reduced by 16% in the TR-LC plots and by 23% in the TR-HC plots; height was reduced by 9% in the TR-HC plots.

Volume per tree was reduced by 30% in the TR-LC plots, and by 42% in the TR-HC plots. The degree of compaction did not have a significant effect on tree volume in the plots where litter had been removed but did have a significant effect where the topsoil had been removed. Volume per tree was 17% less in the high compaction plots (TR-HC) than in the low compaction plots (TR-LC). Volume per hectare was reduced by 29% in the TR-LC plots and by 45% in the TR-HC plots but other treatments were not significantly different from the control plots.

3.1.2 Economic Potential at Age 21

Economic potential was not affected, on either a per hectare basis or a per tree basis, by removal of the litter layer at the time of planting (Table 2). Treatments where the topsoil had been removed and/or compaction had occurred did have signifi-

Table 2. Key radiata pine measured and calculated variables at age 21.

Treatment[a)]	Diameter breast height (cm)	Height (m)	Tree volume (m^3 per tree)	Stand volume (m^3 ha^{-1})	Stand economic potential (NZ$ ha^{-1})	Tree economic potential (NZ$ per tree)
TR-HC	39.2 a	28.7 a	1.21 a	324 a	13514 a	57 a
TR-LC	42.4 b	30.2 b	1.46 b	414 b	20485 a	74 ab
LR-LC	48.8 c	31.1 bc	1.93 c	550 c	27552 b	97 b
LR-NC	50.0 c	31.8 c	2.05 c	582 c	35290 c	124 c
Control	50.7 c	31.6 c	2.10 c	586 c	38608 c	142 c

a) Treatment means with the same letter are not significantly different at the $p<0.05$ level. Means have been adjusted for an average stocking of 285 stems ha^{-1} using number of stems per hectare as a covariate.

Table 3. Log product yield distributions at age 21 for each soil disturbance treatment

Treatment	Pruned domestic and export sawlogs	Unpruned export sawlogs: A & K grades	Unpruned domestic sawlogs: small and large branch grades	Pulp logs	Stumps and cutting waste [a)]
	% of total volume per treatment				
TR-HC	0	55	14	26	5
TR-LC	2	58	14	21	4
LR-LC	4	44	24	21	7
LR-NC	11	43	27	15	5
Control	16	49	16	14	4

a) Differences between treatments will be due to differences in tree characteristics such as tree size (diameter, height and taper) and quality, and to the bucking patterns selected to maximize value.

cantly lower economic potential than the Control. LR-LC was lower by about NZ$11 000 ha^{-1} (NZ$45 per tree); TR-LC was lower by about NZ$18 100 ha^{-1} (NZ$68 per tree); and TR-HC was lower by about $25 100 ha^{-1} (NZ$85 per tree). It is important to stress that harvested areas are usually made up of a mosaic of disturbance classes, the majority being undisturbed and equivalent to the Control treatment. To determine what the total impact on economic potential would be, it would be necessary to sum the per treatment values after they have been weighted by the proportion of the harvest unit in each disturbance class. The proportion of a harvest unit that ends up in each disturbance class depends upon many factors, including such things as planning, equipment type, how the equipment is operated, soil conditions, weather conditions, etc.

3.1.3 Log Product Yields at Age 21

As well as total volume per hectare being affected by treatment, so too were the distributions of log product yields (Table 3).

Pruned domestic and export sawlogs are the most valuable log products. Yields of these log types decreased from 16% to 0% as the severity of the soil disturbance increased. Pruned log yields from each tree are affected by 1) whether the tree was initially selected for pruning and was pruned to a height that was sufficient to meet pruned-log, length specifications (small, malformed trees are less likely to be selected), 2) whether the tree had grown sufficiently to meet the minimum small end diameter specification for pruned logs, and 3) whether the most valuable combination of logs that could be cut from the tree included a pruned log. Each of these conditions is either directly or indirectly affected by soil disturbance.

Pulp logs are the least valuable log products. Pulp log yields increased from 14% to 26% with increasing soil disturbance severity.

Overall yields of unpruned domestic and export sawlogs were similar, ranging from 65% to 73% of total volume. Soil disturbance, however, did affect which markets would be supplied in an indirect way. The unpruned export grade sawlogs used in the analyses had longer length requirements than the unpruned domestic grade sawlogs. If pruned logs could not be cut from a tree (e.g. TR-HC treatment), the next most valuable thing to do would be to cut long length export grade sawlogs in preference to shorter length unpruned domestic grade sawlogs. Yields of unpruned export grade logs were about 5% to 10% higher than the Control for treatments where the topsoil had been removed and subsoil compacted (TR-LC and TR-HC). Yields of unpruned export grade logs were about 5% lower for the treatments where the litter had been removed. Yields of unpruned domestic grade sawlogs were similar (14%) to the Control for the TR-LC and TR-HC treatments but about 10% higher for the LR-NC and LR-LC treatments.

3.2 Long-Term Growth Trends to Age 21

The relative differences between the Control and the soil disturbance treatments on volume per tree decreased with time (Fig. 1) although the

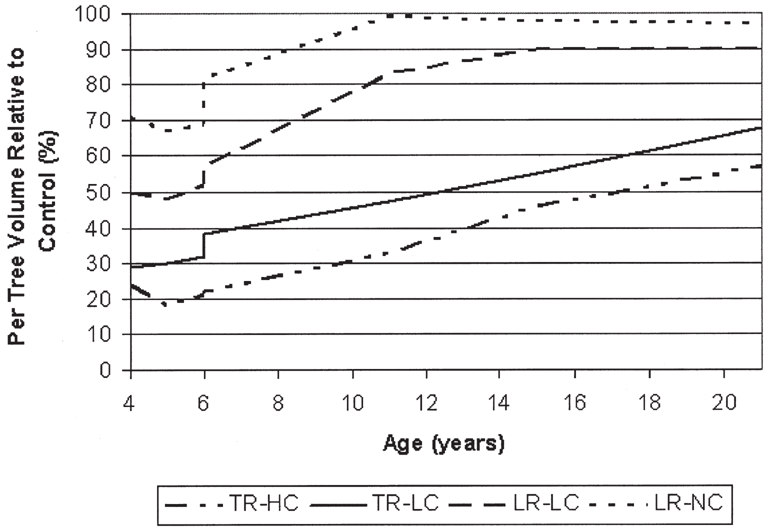

Fig. 1. Long-term impacts of soil disturbance on tree volume growth from age 4 (post-thinning) through age 6 (pre- and post-thinning) to age 21 relative to Control (100%). TR-HC = Topsoil removed, high compaction; TR-LC = Topsoil removed, low compaction; LR-LC = Litter removed, low compaction; LR-NC = Litter removed, no compaction.

absolute differences tended to increase. Absolute differences are provided below in parentheses, m^3 per tree, as additional information to the relative differences. At age 4 the difference between the LR-NC treatment and the Control was 29% (0.01 m^3). This difference decreased to 18% (0.01 m^3) by age 6 (post-thinning) and to 1% (0.01 m^3) by age 11. The difference at age 21 was 3% (0.05 m^3) and not significant. Relative differences dropped from 50% (0.01 m^3) at age 4 to 8% (0.17 m^3) at age 21 for the LR-LC treatment. Relative differences dropped from 71% (0.02 m^3) to 30% (0.64 m^3) for the TR-LC treatment for ages 4 and 21 years respectively. Relative differences dropped from 76% (0.02 m^3) to 42% (0.89 m^3) for the TR-HC treatment for ages 4 and 21 years respectively.

At age 11 the mean heights of LR-LC, TR-LC and TR-HC trees were significantly different from the control (Murphy et al. 1997). By age 21 only the TR-LC and TR-HC treatments had mean heights that were significantly lower than the Control.

3.3 Projected Impacts of Soil Disturbance to Age 28

3.3.1 Economic Potential at Age 28

By age 28 it is projected that trees planted in the Control plots will be worth about NZ$260 per tree or a little over NZ$65 000 ha^{-1} (Table 4). It is expected that economic potential will be significantly affected at age 28 by the LR-LC, TR-LC and TR-HC disturbance treatments for both the SG or NG trajectories. Economic potential will be reduced by as much as NZ$160 per tree or NZ$46 000 ha^{-1} depending on the treatment and growth trajectory assumed.

Reductions in per hectare economic potential of 29%, 49% and 70% are projected using the SG trajectory for the LR-LC, TR-LC and TR-HC disturbance treatments respectively. If the NG trajectory is assumed these reductions are lower at 26%, 35% and 64% respectively.

The maximum amounts that could be spent to either prevent soil disturbance or undertake remedial action are shown in the fourth column

Table 4. Stand and tree economic potential grown forward to age 28.

Treatment [a]	Stand economic potential (NZ$ ha^{-1})	Tree economic potential (NZ$ per tree)	Drop in projected net present value compared with the control (NZ$ ha^{-1})
Same basal area % gap (SG) growth trajectory [b]			
TR-HC	19469 a	96 a	18960
TR-LC	35040 b	131 ab	12601
LR-LC	46556 c	166 b	7898
LR-NC	61772 d	216 c	1683
Control	65894 d	257 c	-
Narrowing basal area % gap (NG) growth trajectory [b]			
TR-HC	23413 a	117 a	17139
TR-LC	42520 b	156 b	9336
LR-LC	48188 c	172 b	7021
LR-NC	60886 cd	214 c	1835
Control	65380 d	257 d	-

[a] Treatment means with the same letter are not significantly different at the $p < 0.05$ level. Means have been adjusted for an average stocking of 285 stems ha^{-1} using number of stems per hectare as a covariate.
[b] SG growth trajectory = trees grow from age 21 to age 28 in such a way that the same percentage gaps are maintained between the average basal areas of the Control and the disturbance treatments on a per hectare basis as at age 21. NG growth trajectory = growth based on a narrowing basal area gap as indicated by trends over the decade from age 11 to age 21.

of Table 4 for all treatments. Since the treatments where topsoil had been removed and/or compaction occurred (LR-LC, TR-LC and TR-HC) were the only ones that had per hectare economic potentials that were statistically lower than the Control, these are the ones where attention is now focused. Under an SG growth trajectory, the maximum amount that could be spent is about NZ$19 000 ha^{-1} on TR-HC areas, about NZ$12 600 ha^{-1} on TR-LC areas, and about NZ$7900 ha^{-1} on LR-LC areas. Under an NG growth trajectory, the maximum amount that could be spent is about NZ$17 100 ha^{-1} on TR-HC areas. Since only a small portion of a harvest unit is likely to have its topsoil removed and/or be compacted, only a portion of these costs could be incurred by a landowner to mitigate or prevent soil disturbance.

3.3.2 Log Product Yield Distributions at Age 28

In general terms, product yield distributions changed as a result of growing the trees from age 21 to age 28. Expressed as a percentage of total volume, unpruned export grade sawlogs and pulp logs decreased in quantity, pruned domestic and export sawlogs were unchanged, and unpruned domestic sawlogs increased.

The ranking between treatments for particular product classes for the SG growth trajectory was similar to that found at age 21, except for the unpruned domestic grade sawlogs. Pruned domestic and export sawlogs decreased from 17% to 0% as the severity of the soil disturbance increased. Pulp log yields increased from 11% to 21% with increasing soil disturbance severity. Overall yields of unpruned domestic and export sawlogs were similar, ranging from 70% to 79% of total volume. Yields of unpruned export grade logs were about 15% higher than the Control for treatments where the topsoil had been removed and subsoil compacted (TR-LC and TR-HC). Yields of unpruned domestic grade sawlogs were about 10% lower than the Control for the TR-LC and TR-HC treatments but similar (42%) for the LR-NC and LR-LC treatments.

4 Discussion and Conclusions

Skinner et al. (1989) reported that tree growth reduction due to treatment was evident during the first five years of this trial. They attributed growth losses to degraded soil physical conditions and to soil fertility, and noted that "early effects of physical site degradation on the growth of *Pinus radiata* resulted from a combination of nutrient (N and P) deficiency, increases in soil compaction (soil resistance), and less favourable soil temperatures owing to the absence of a buffering effect of the forest litter". Simcock et al. (in review) reported that, by mid-rotation (age 15), tree volume on the litter removed plots had recovered "probably due to canopy closure and development of a new litter layer creating a favourable microclimate (modifying soil temperature) and recycling nutrients". They also noted that tree volumes were reduced due to reduced total carbon, total nitrogen and soil air capacity in the treatments where topsoil was removed and subsoil compacted.

Three quarters of the way through the rotation at age 21 years, height, diameter and volume per tree continue to be affected on the plots where the topsoil had been removed and the subsoil compacted. Relative to the undisturbed sites (Control), tree height was reduced by at least 4% (1.4 m), tree diameter by at least 16% (8 cm) and tree volume by at least 30% (0.64 m^3). The degree of subsoil compaction (high or low) affected diameter, height and tree volume growth on sites where the topsoil had been removed. Removing the litter layer at the time of harvest had no impact on diameter, height, or tree volume growth whether there was low compaction or no compaction. What was not investigated in this study was the potential influence of soil disturbance on stem taper. If stem taper is influenced by soil disturbance, volume impacts could be greater or lesser than reported in this paper.

The economic and marketing impacts of soil disturbance were greater on a percentage basis than the impacts on volume growth. Soil disturbance reduced the economic potential at age 21 by up to NZ$25 100 ha^{-1} (65%) or NZ$85 per tree and substantially altered the distribution of product yields that could be harvested. The losses in economic potential were projected to be up to NZ$45 400 ha^{-1} (70%) or NZ$160 per tree at harvest time (age 28) on the severely disturbed sites (TR-HC). Losses would be less on the sites where litter had been removed or where compaction was low. Losses in economic potential were due to reductions in tree size and total volume per hectare, a decrease in high-value pruned log yields, and an increase in low-value pulp log yields.

Recent nutrient equilibria work suggests that the sites with limited disturbance will return to "normal" by about age 30+ (Zabowski et al. 1996). Although the soils appear to be recovering and the gaps between the undisturbed sites and the treatments narrowing, it is unlikely that the severely disturbed sites will recover by harvest time. To maintain site potential the forester is, therefore, faced with either preventing soil disturbance or remedial action after disturbance has occurred.

Sites where the topsoil has been removed and the subsoil compacted are the ones that have significantly reduced economic potential. This research indicates that NZ$9300 to NZ$19 000 ha^{-1} could be spent to ameliorate these sites or could be spent on harvesting practices that prevent topsoil removal and subsoil compaction. The reader should note at this point that these expenditures relate only to a portion of each harvest setting, since the whole area is not likely to have all of the topsoil removed and subsoil compacted. Murphy (1984) noted in a survey of 19 harvesting sites in New Zealand, that the amount of "deep" disturbance, equivalent to TR-LC and TR-HC, varied according to many factors, such as planning, machinery employed and slope, but was typically in the range of 5 to 25%. The amount that could be spent to ameliorate whole harvest settings would therefore be one-twentieth to one-quarter of the values noted above; i.e. from as low as NZ$400 ha^{-1} to as high as NZ$4800 ha^{-1}.

As with most field trials, there are limitations associated with this research. Firstly, the work has been carried out on one soil type and may not be applicable to other soil types. Secondly, the differences found between the undisturbed control and the heavily disturbed areas may be greater than would be found in practice since weeds were controlled throughout the duration of this trial. Murphy and Firth (2004) found in operational trials that weed growth was influenced by soil disturbance with the greatest weed growth and, therefore, competition for tree growth, occurring on undisturbed areas and the least on heavily disturbed areas. Thirdly, differences between the undisturbed control and the heavily disturbed areas may be less than would be found in practice since the treatments were established on relatively large (600 m^2), rectangular blocks, which do not truly reflect the irregular mosaic of disturbance classes found after a harvesting operation, and each treatment received similar management practices. In the same operational trials referred to above, Murphy and Firth (2004) found that soil disturbance also influenced the early management of trees. Trees planted on heavily disturbed areas were less likely to be selected for low pruning and more likely to be selected for pre-commercial thinning.

Despite these limitations the Maramarua trial does provide an improved understanding of the consequences of soil disturbance on economic return. The authors are unaware of any studies that have followed the impacts of soil disturbance on tree growth, economic potential and log product yields from seedling establishment through to harvest. Projections have been made on the likely impacts at rotation end based on assessments three-quarters of the way through the rotation. It is vital now that the impacts of soil disturbance on *Pinus radiata* be monitored in the Maramarua trial through to the end of the rotation.

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